EEC 4230 - Mobile Communication Systems

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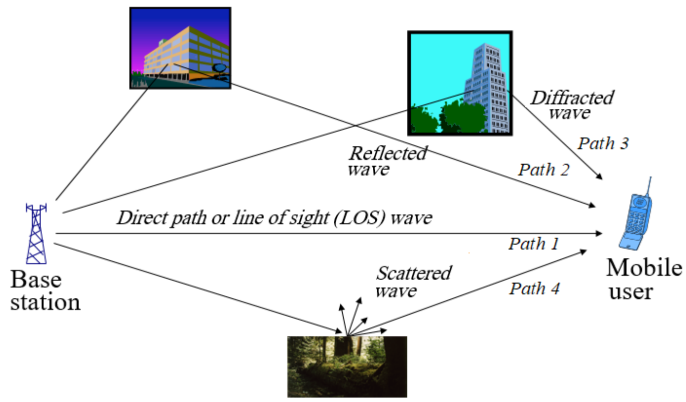
Lecture 6: Mobile propagation: Small-scale multipath fading-I

Outline



- Small-scale fading (simply fading) describes rapid fluctuations of a radio signal over a short period of time (few seconds) or a short travel distance (few λs).
- Radio waves from the transmitter arrive at the mobile from different directions, each with different amplitude and propagation delays (multipath components).
- Multipath components may combine (vectorial addition) either constructively or destructively at the mobiles, and may thus cause the signal received by the mobile to distort or fade (small-scale fading).

Factors causing small-scale fading:

- Multipath propagation: presence of reflectors, scatterers... in the environment.
- Speed of the mobile: movement of transmitter or receiver or both cause frequency shift in the transmitted signal (called Doppler shift).
- Speed of surrounding object: movements of surrounding objects induce time-varying Doppler shift.
- Transmission bandwidth of the signal: If the transmitted radio signal has bandwidth greater than the bandwidth of the multipath channel.

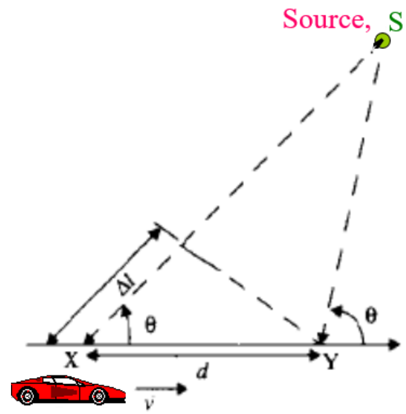
Doppler Shift:

- Consider mobile moving at constant velocity, v, along a path segment of length d between points A and B, while it receives signals from a remote source S.
- The phase shift in the received signal due to the difference in path length as the mobile moves from points A to B is given by:

$$\Delta\phi = \frac{2\pi\Delta L}{\lambda} = \frac{2\pi d}{\lambda}\cos\theta = \frac{2\pi\nu\Delta t}{\lambda}\cos\theta$$

Doppler Shift:

- The apparent change in frequency (Doppler shift or Doppler frequency) is $f_D = \frac{v}{\lambda}\cos\theta$.
- Positive Doppler shift (apparent received frequency is increased): receiver moves towards transmitter.
- Negative Doppler shift (apparent received frequency is decreased): receiver moves away from transmitter.
- If source transmits fc, the received frequency is $f_c \pm f_D$



- Phase shift between A and B:

$$\boxed{\Delta\phi = \frac{2\pi\,\Delta L}{\lambda} = \frac{2\pi\ d}{\lambda}\cos\theta = \frac{2\pi\ v\Delta t}{\lambda}\cos\theta}$$

- Frequency shift between A and B (Doppler frequency):

$$\boxed{f_D = \frac{1}{2\pi}\frac{\Delta\phi}{\Delta t} = \frac{v}{\lambda}\cos\theta}$$

Example 1:

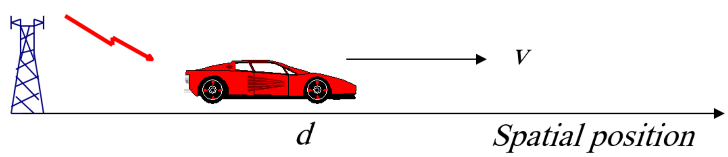
Consider a transmitter which radiates a sinusoidal carrier frequency of 1850 MHz. For a vehicle moving at 28 m/s, compute the received carrier frequency if the mobile is moving:

1. Directly toward the transmitter.
2. Directly away from the transmitter.
3. In a direction perpendicular to the direction of arrival of the transmitted signal.

Solution

1. $\lambda = c/f = 0.162$ m, $f_D = 28/0.162 = 172.84$ Hz, $f = f_c + f_D = 1850.000172$ MHz.
2. $\lambda = c/f = 0.162$ m, $f_D = 28/0.162 = 172.84$ Hz, $f = f_c - f_D = 1849.999827$ MHz.
3. In this case $\theta = 90$ and $\cos\theta = 0$, and there is no Doppler shift. The received signal frequency is the same as the transmitted frequency

- Modeling the impulse response of wireless channels allows numerical performance evaluation of different mobile communication systems.
- For a mobile at a fixed position, d, the received signal can be expressed as: $y(d,t) = x(t) * h(d,t) = \int_{-\infty}^{\infty} x(\tau)h(d,t-\tau)d\tau$
- For a causal system, (i.e. $h(t) = 0, t < 0$), $y(d,t) = \int_{-\infty}^{t} x(\tau)h(d,t-\tau)d\tau$
- Assume the mobile moves at a constant velocity v, then $d = vt$, thus $y(vt,t) = \int_{-\infty}^{t} x(\tau)h(vt,t-\tau)d\tau$ or $y(t) = x(t) * h(t,\tau)$ where $x(t)$ = transmitted bandpass signal modulated at carrier frequency f_c $y(t)$=received signal, $h(t,\tau)$ = impulse response of the multi-path radio channel, t= time variable, τ channel multipath delay for fixed t.
- The impulse response of a multipath channel can be expressed as: $h(t,\tau) = \sum_{k=0}^{N-1} a_k(t,\tau)e^{j\theta_k(t,\tau)}\delta(\tau - \tau_k(t))$

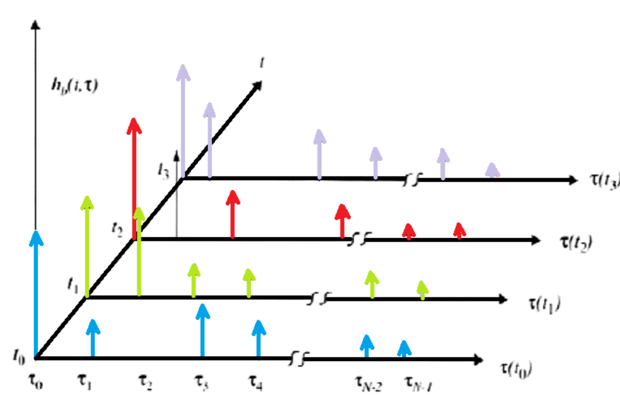


Impulse response model of a multipath channel

- $a_k(t,\tau)$ is the amplitude of the k^{th} multipath component at time t.
- $\tau_k(t)$ is the excess delay of the k^{th} multipath component at time t.
- $\theta_k(t,\tau)$ is the phase shift of the k^{th} multipath component, which is a function of the delay τ and time t.
- N is the number of paths.

If the channel is assumed to be time invariant, or stationary over a small-scale time or distance interval (quasi-static fading), then:

$$h(t,\tau) = \sum_{k=0}^{N-1} a_k e^{j\theta_k}\delta(\tau - \tau_k)$$



$$h(t,\tau) = \sum_{k=0}^{N-1} a_k(t,\tau)e^{j\theta_k(t,\tau)}\delta(\tau - \tau_k(t))$$

Impulse response Measurements

Cellular operators develop channel impulse response for different environments to allow prior planning and design. – typical entry level duties given wireless Engineers

Small-scale Multipath channel Measurements techniques

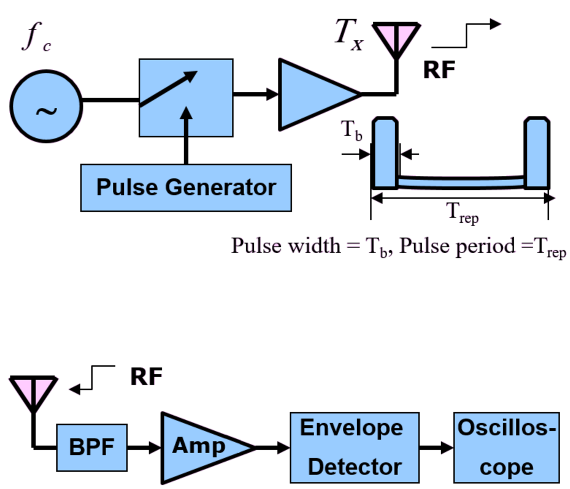
- Small-scale channel state for an environment is typically recorded in the form of average power delay profiles, defined as $P(\tau) = E_k[|h(t_k, \tau)|^2]$, where $E_k[.]$ denotes ensemble average over samples taken at different times t_k.
- Different channel sounding techniques for estimating the power delay profiles of wireless systems are
  (1) Direct RF pulse system
  (2) Spread Spectrum based channel sounding
  (3) Frequency domain channel sounding

Direct RF pulse channel sounding

It transmits a repetitive pulse of width T_b , and uses a receiver with a wide bandpass filter to collect all multipath signal received from each of these pulses and take the ensemble average.

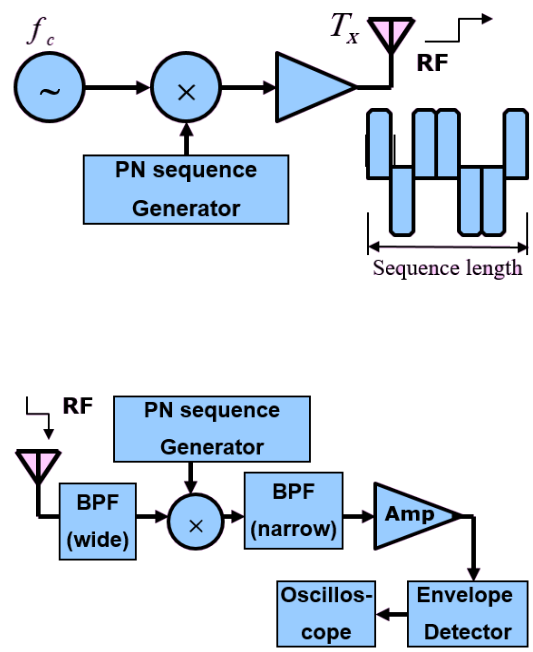
Advantage:
Low complexity (easily implemented).

Disadvantage:
It is subject to interference and noise in the environment during the test which may not represent the actual channel being measured.



Spread Spectrum based channel sounding

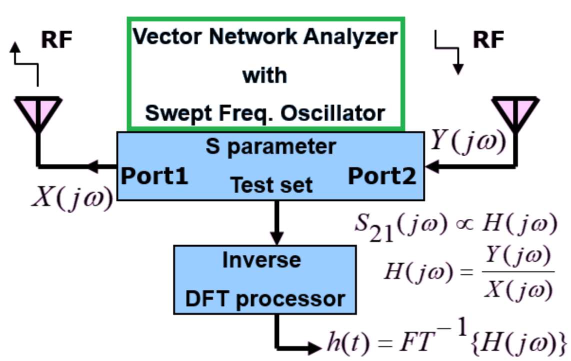
Rather than transmitting ordinary pulses, the transmitted pulses in this approach are encoded using binary PN (pseudo-noise) sequence, which spreads the pulse over a wide band causing noise & interference rejections.



Advantage:
(1) Moderate complexity, and noise/ interference rejection.
(2) Processing gain of the SS system allows much lower power than the direct RF pulse system.
(3) Widely used for indoor and outdoor channel sounding (3G and 4G).
Disadvantage:
Isnstantaneous measurements (real time) are not made, but over PN sequence length

Frequency domain channel sounding

This method measures channel impulse response in frequency-domain and use Inverse Discrete Fourier Transform (IDFT) to convert from frequency to time domain measurements. The S parameter measured in frequency domain is proportional to $H(j\omega) = FT\{h(t)\}$.
Advantage:
Provides amplitude & phase information of the time-domain channel (complex).
Disadvantage:
Hardware synchronization is needed between transmitter & receiver, making it useful only for very close measurement. Used in experiments on indoor channel measurements.

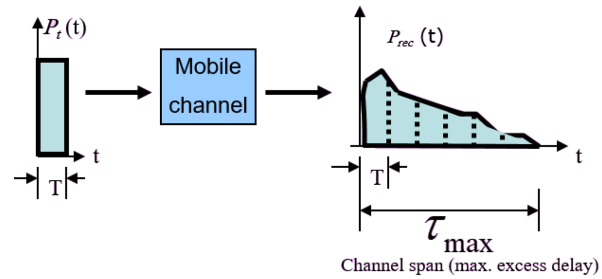


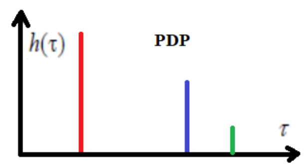
Parameters of mobile multipath channel

Quantitative multipath channel parameters have been developed in order to compare different multipath channels and for receiver design purposes.

(1) Time dispersion parameters

- Mean Excess delay: $\bar{\tau} = \frac{\sum_{k=0}^{N-1} \alpha_k^2 \tau_k}{\sum_{k=0}^{N-1} \alpha_k^2}$
- RMS delay spread:
  $\sigma_\tau = \sqrt{\bar{\tau^2} - (\bar{\tau})^2}$
  where $\bar{\tau^2} = \frac{\sum_{k=0}^{N-1} \alpha_k^2 \tau_k^2}{\sum_{k=0}^{N-1} \alpha_k^2}$
- Maximum excess delay τ_{max} (x dB): Is the time delay during which multipath energy falls to x dB below the maximum.



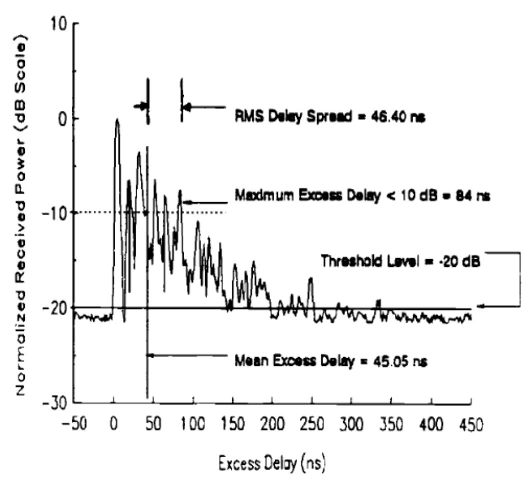


These parameters are obtained directly from power delay profile (PDP).

Parameters of mobile multipath channel

Environment	Frequency (MHz)	RMS Delay Spread (σ_τ)	Notes	Reference
Urban	910	1300 ns avg. 600 ns st. dev. 3500 ns max.	New York City	[Cox75]
Urban	892	10-25 μs	Worst case San Francisco	[Rap90]
Suburban	910	200-310 ns	Averaged typical case	[Cox72]
Suburban	910	1960-2110 ns	Averaged extreme case	[Cox72]
Indoor	1500	10-50 ns 25 ns median	Office building	[Sal87]
Indoor	850	270 ns max.	Office building	[Dev90a]
Indoor	1900	70-94 ns avg. 1470 ns max.	Three San Francisco buildings	[Sei92a]

Typical values of RMS delay spread for indoor/outdoor radio channels



Indoor PDP; RMS delay spread σ_τ, mean excess delay, maximum excess delay (10dB)

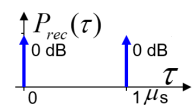
Parameters of mobile multipath channel

(1) Time dispersion parameters

- Coherence bandwidth B_c: is the range of frequencies over which the channel can be considered "flat" (i.e., the channel's frequency response stays correlated).
- B_c is inversely proportional to RMS delay spread, but its exact value depends on how it is defined:-
- (1) If the coherence bandwidth is defined as the bandwidth over which the frequency correlation function is above 0.9, then $B_c = \frac{1}{50\sigma_\tau}$
- (2) If the coherence bandwidth is defined as the bandwidth over which the frequency correlation function is above 0.5, then $B_c = \frac{1}{5\sigma_\tau}$
- One good rule of thumb is that the RX doesn't need an equalizer if $\sigma_\tau \leq 0.1T_s$

Example 2:

Compute the RMS delay spread for the power delay profile of a multipath channel shown below. What is the maximum symbol rate that can be transmitted through the channel without needing an Equalizer?.



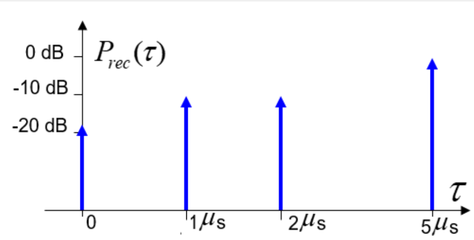
Solution

$\sigma_\tau = 0.5$ μsec, and $R_s = 200$ k Sym/sec. For BPSK, $R_b = R_s$

Parameters of mobile multipath channel

Example 3:

Calculate the mean excess delay, and the RMS delay spread for the multipath power delay profile shown below. Estimate the 50% coherence bandwidth of the channel. Would this channel be suitable for AMPS or GSM cellular service without the use of an Equalizer?.



Solution

$\bar{\tau} = 4.38$ μsec, $\sigma_\tau = 1.37$ μsec, and B_c (50%)= 146 KHz.
(1) Bc>30kHz used in AMPS (no Equalizer required)
(2) But Bc<200kHz used in GSM (Equalizer required for GSM).

Parameters of mobile multipath channel

Delay spread, σ_τ, and coherence bandwidth, B_c, describe the time dispersion of the channel in a short time window. However, they do not give information about the time-varying nature of the channel.

(2) Frequency dispersion parameters

- Doppler spread (B_D) and coherence time (T_C): Both describe the effect of time-varying nature of the channel on the received signal.
- Doppler spread B_D is a measure of the spectral broadening caused by the time rate of change of the mobile radio channel: $B_D = f_D = \frac{v}{\lambda}$
- If the baseband signal bandwidth is much greater than B_D, then the effects of the Doppler spread are negligible.
- Coherence time is a statistical measure of time duration over which the channel impulse response is essentially invariant: $T_c \propto \frac{1}{B_D}$
- If is defined as the time over which the time correlation function is above 0.5, then $T_c \approx \frac{9}{16\pi f_{D_{max}}}$

Parameters of mobile multipath channel

Example 4:

A measurement team traveling at 50 m/s uses a 900 MHz carrier to estimate the small-scale propagation parameter for an urban environment:

1. What is the Doppler spread B_D for the mobile channel,
2. What is the coherence time T_c for the mobile channel.

Solution

1. $B_D = 3 \times 50$ Hz
2. $T_c = \frac{3}{50 \times 16\pi}$ seconds

Types of small-scale fading

- Depending on the relation between the signal parameters (such as bandwidth, symbol period, etc) and the propagation channel parameters (such as RMS delay spread and Doppler spread), transmitted signals will undergo different types of small-scale fading.
- Basically there are two fading mechanisms, one independent of the other

Flat fading

- Signal BW, B_s < Channel BW, B_c
- Symbol period, T_s> Delay spread, σ_τ

Frequency selective fading

- Signal BW > Channel BW
- Symbol period < Delay spread

Fading based on multipath delay spread

Fast fading

- Symbol period, T_s> Coherence time, T_c
- Ch variations faster than signal

Slow fading

- Symbol period < Coherence time item Ch variations slower than signal

Fading based on Doppler spread

Types of small-scale fading

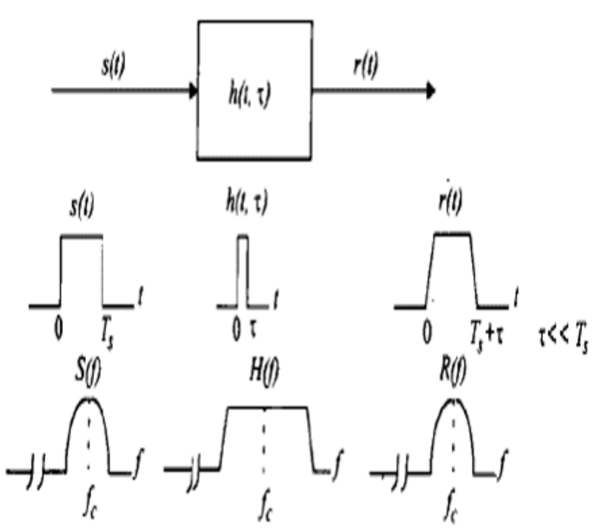


Illustration of flat fading

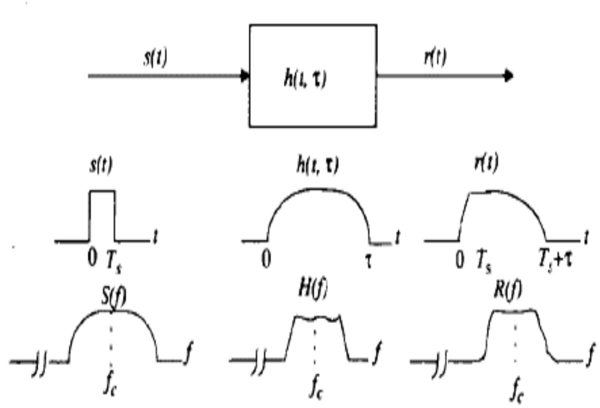


Illustration of frequency selective fading